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Physical Exercise Interventions for Emerging Adults with Attention-Deficit/Hyperactivity Disorder (ADHD)

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Attention-deficit/hyperactivity disorder (ADHD) is characterized by deficits in executive functioning (e.g., working memory, response inhibition, and organization; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Inattention and hyperactivity/impulsivity result in impairments in academic, occupational, and social functioning (American Psychiatric Association [APA], 2013). The primary treatments for ADHD include psychosocial, pharmacological, and combined treatments. Despite the well-documented effectiveness of these interventions, there are limitations to their use. Although both pharmacotherapy and psychosocial treatments are efficacious during active treatment (Knight, Rooney, & Chronis-Tuscano, 2008; Spencer et al., 1996), few individuals receive long-term treatment, resulting in limited, if any, sustained effects (Molina et al., 2009). One explanation for the transient benefits of current treatments is that they target symptoms and functional impairments rather than the neural mechanisms that underlie the disorder (Berwid & Halperin, 2012). In response to this, researchers have begun to consider other forms of interventions to directly impact these underlying deficits.

Physical exercise has received increasing attention with the current obesity epidemic (e.g., Davis et al., 2011). The benefits of physical exercise include improving medical problems (e.g., obesity, diabetes) and psychological difficulties (e.g., anxiety, depression; Hillman, Erickson, & Kramer, 2008). A growing body of research suggests physical exercise has powerful effects on neurocognitive, psychological, and academic functioning (Hillman et al., 2008; Trost, Owen, Bauman, Sallis, & Brown, 2002). Emerging from this burgeoning evidence, mental health researchers have begun to explore exercise as an avenue by which mental health treatment outcomes can be enhanced.

Among individuals with ADHD, exercise may not only improve cognitive performance (Berwid & Halperin, 2012; Gapin, Labban, & Etnier, 2011), but

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ameliorate comorbid anxiety and depression (Salmon, 2001), and serve as a protective factor for adverse health outcomes (Nigg, 2013)—all of which commonly co-occur with ADHD (Barkley, Murphy, & Fischer, 2008). Indeed, initial results with children and adolescents have been promising. Findings from these studies provided preliminary evidence that exercise may improve motor, cognitive, social, and behavioral functioning for school-aged children with ADHD (Neudecker, Mewes, Reimers, & Woll, 2015). While investigations on interventions involving exercise for school-aged children with ADHD advance, there are no known studies examining the use of such interventions for ADHD among *emerging adults* (ages 18–25; Arnett, 2000).

Although tempting, before generalizing school-aged treatment research to emerging adults, there are several important developmental and environmental differences that must be considered. For example, emerging adults experience higher demands for self-regulation, have greater autonomy, diminished external support (e.g., parents, schools), and their neurological structures are near their peak maturity (Giedd, 2004). Thus, tailoring school-aged interventions to the developmental and environmental context of emerging adulthood is warranted to evaluate possible treatment effects.

We summarized research across disciplines to elucidate the relation between exercise and ADHD–related impairment in the developmental context of emerging adulthood. We also incorporated research on possible mechanisms of change specific to ADHD and exercise interventions for depression—the mental health area with which the literature is most robust—to understand the strengths and weaknesses of this therapeutic approach outside of childhood. We conclude with clinical implications and recommendations, as well as avenues for future research.

PHYSICAL FITNESS, ACTIVITY, AND EXERCISE

A robust literature suggests that physical fitness, physical activity, and physical exercise have powerful effects on the structure, function, and development of the brain over both the short term and the long term (Best, 2010; Hillman et al., 2008; Portugal et al., 2013; Tomporowski, Lambourne, & Okumura, 2011). However, these terms are often confused with one another and are often used interchangeably even though they describe different concepts. The following section provides definitions and methods for quantifying physical fitness, physical activity, and physical exercise as outlined by the Centers for Disease Control and Prevention (CDC; see Casperson, Powell, & Christenson, 1985).

Physical Fitness

Whereas physical activity and physical exercise are related to the movements that people perform, *physical fitness* corresponds to attributes people have or achieve. Being physically fit has been broadly described as the ability to complete daily tasks with vigor and alertness, with ample energy to enjoy leisure pursuits and meet unforeseen emergencies. Many quantifiable components contribute to physical fitness and are categorized as being skill- or health-related fitness.

Skill-related components of physical fitness and can be categorized into six components: (1) agility, (2) balance, (3) coordination, (4) speed, (5) power, and (6) reaction time. There are many methods for measuring each of the six components of skill-related physical fitness, including: weaving through cones, balancing on one leg, throwing and catching a ball, sprints, jumping up on a box, and hitting a thrown baseball with a bat, respectively.

The five health-related components of physical fitness include: (1) cardiovascular endurance, (2) muscular endurance, (3) muscular strength, (4) body composition, and (5) flexibility. Similar to skill-related physical fitness, there are multiple methods for measuring each of the components of health-related physical fitness, including: a 12-minute run, sit-ups, handgrip dynamometer, body mass index, and sit-and-reach test, respectively.

Physical Activity

Physical activity is any bodily movement contrived by skeletal muscles that results in energy expenditure above the basal metabolic rate. This includes, but is not limited to, physical activity occurring at work (e.g., sitting, standing, lifting), leisure (e.g., household tasks, sports, metabolic conditioning exercises), and while sleeping.[1] Energy expenditure is often measured in kilocalories (kcal) or kilojoules (kJ) and can be expressed as a total amount of energy used in a given physical activity and rate (kcal per unit of time). The net amount of energy used with a physical activity is associated with the amount of muscle mass used to produce bodily movements and the intensity, duration, and frequency of muscular contractions.

Physical Exercise

Although the terms *physical activity* and *physical exercise* have many common elements, these terms are not synonymous. *Physical exercise* is any physical activity that is planned, structured, and repetitive with the intention to develop or maintain physical fitness (e.g., strength, flexibility, aerobic endurance). Therefore, physical exercise is a subtype of physical activity and may compose all or part of different physical activities, except for sleep. For example, the physical activity of playing sports is often purposefully performed to improve or maintain physical fitness and is often planned, structured, and repetitive. Conversely, household and work tasks are often completed in a labor-saving manner. That is, the goals of these physical activities are often completed with the goal of energy conservation, with little to no regard to physical fitness and would therefore be classified as physical activity. However, a person may plan or structure the performance of household or work tasks in a labor-inducing manner to “burn” more calories or develop muscular strength. When tasks are performed in this manner, they are considered physical exercise.

The terms *physical activity* and *physical exercise* are often conflated in the ADHD literature, which obfuscates interpretations of empirical research. This is compounded by the broad range of physical activities/exercises in school-aged ADHD studies, which include aquatic exercise (Chang, Hung, Huang, Hatfield, & Hung, 2014), plyometric exercise (tuck jumps, one-leg hops; McKune, Pautz, & Lomjbard, 2004), 20 minutes of walking (Taylor & Kuo, 2009), recumbent cycling (Piepmeier et al., 2015), yoga (Jensen & Kenney, 2004), and sports (basketball, soccer, tennis; Pan et al., 2015; Verret, Guay, Berthiaume, Gardiner, & Béliveau, 2012). This diversity of methods results in variable intensity, duration, and frequency of interventions across studies, precluding uniform comparison of the effects of physical activity interventions (e.g., walking rather than being driven to school) and physical exercise interventions (e.g., participating in vigorous aerobic activity) for children and adolescents with ADHD. However, because most investigations on this topic use interventions methods that satisfy all or most of the definitional criteria for physical exercise (PE), this term will be used to refer to both physical exercise and physical activity for the remainder of the article.

NEUROPSYCHOLOGY OF ADHD

Over the last 10 years, several meta-analyses have been performed on different aspects of cognition and neurobiology of ADHD (e.g., Hervey, Epstein, & Curry, 2004; Schoechlin & Engel, 2005; Willcutt et al., 2005; Willcutt et al., 2012; Woods, Lovejoy, & Ball, 2002). The following section is a summary of the cognitive and neurobiological mechanisms implicated in the manifestation of ADHD (for a detailed review, see Willcutt, 2015).

Cognitive Factors Related to ADHD

Prevailing cognitive models suggest that ADHD arises from general weaknesses in executive functioning (EF)—a set of “top-down” cognitive processes used to regulate behavior toward adaptive, long-term goals (Barkley, 1997). Specific EF processes implicated in ADHD include the ability to inhibit impulses (inhibition), short-term storage and manipulation of information (working memory), and preferring smaller, immediate rewards over larger, delayed rewards (delay aversion; Willcutt et al., 2012). Across the lifespan, meta-analyses report medium to large differences among groups with and without ADHD across these EF tasks ($d = .50–.70$; Willcutt, 2015). However, the patterns of cognitive impairments observed in ADHD are inconsistent across individuals.

Even though individuals with ADHD are 3 to 4 times more likely to exhibit significant deficits in EF than those without ADHD, less than half of individuals with ADHD exhibit significant deficits on any specific EF tasks (Nigg et al., 2005). Similarly, performance in EF tasks tends to correlate significantly with ADHD symptoms but are small in magnitude ($r = .15–.35$; Nigg, Hinshaw, Carte, & Treuting, 1998; Willcutt et al., 2001). Thus, the cognitive processes underlying ADHD are complex and multifactorial, with no single EF deficit being sufficient or necessary to characterize all cases of ADHD (e.g., Pennington, 2006; Willcutt et al., 2010).

Neurobiological Factors Related to ADHD

Consistent with the cognitive literature, studies indicate that there is no single identifiable neurobiological etiology for ADHD. However, models of ADHD posit that neuroanatomical and neurochemical abnormalities in the prefrontal cortex (PFC) underlie much of the cognitive and behavioral manifestations of ADHD (Berridge & Devilbiss, 2011; Durston & Konrad, 2007). The PFC is a region of the brain that is frequently cited as being central to the pathophysiology of ADHD—particularly the frontostriatal and mesolimbic networks (Castellanos & Tannock, 2002; Durston, 2003).

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[1] Although the caloric contribution of physical activity during sleep accounts for a small portion of energy expenditure due to physical activity, the energy used is above basal metabolic rate and is therefore classified as a category of physical activity (Caspersen et al., 1985).

Working memory and inhibition are largely supported by the frontostriatal network, which has links to the cerebellum through the thalamus and is comprised of the lateral prefrontal cortex, dorsal anterior cingulate, and dorsal striatum (Durston, 2003). Structural neuroimaging research has found that adults with ADHD show cortical thinning in the dorsolateral prefrontal and anterior cingulate cortices (Makris et al., 2007). Further, a meta-analysis of neuroimaging studies found a consistent pattern of hypoactivity in the frontostriatal network among children and adolescents with ADHD during tasks requiring working memory and inhibition (Dickstein, Bannon, Xavier Castellanos, & Milham, 2006).

Delay aversion is supported by the mesolimbic network, which connects the ventral striatum (nucleus accumbens), areas of the hippocampus and amygdala, ventral tegmental area, and ventromedial prefrontal regions, which includes the orbitofrontal gyri and anterior cingulate (Sonuga-Barke, 2002). Across studies examining the impact of reinforcement contingencies on ADHD, those with ADHD tend to show atypical physiological responses to rewards, as well as risky decision-making and greater delay aversion (Luman, Oosterlaan, & Sergeant, 2005). Functional neuroimaging studies have reported that individuals with ADHD show lower activation in the ventral striatum when anticipating reward, but higher activation when they received the reward (Scheres, Milham, Knutson, & Castellanos, 2007; Ströhle et al., 2008). Individuals with ADHD also show lower top-down inhibitory control in the orbitofrontal cortex and ventral striatum (Ströhle et al., 2008). Further, structural neuroimaging research has found that adults with ADHD show cortical thinning in the anterior cingulate cortex (Makris et al., 2007).

Neurotransmitter dysfunction has also been implicated in the neurobiological pathology of ADHD (Arnsten, 2009). Dysregulation of dopamine and norepinephrine in the PFC has been suggested to underlie the EF deficits observed in ADHD (Pliszka, 2005). The dopaminergic system, which is associated with motor control, motivation, reward, and affect, is believed to interact with the PFC as a regulation network that is associated with cognitive and behavioral control (Wigal, Emmerson, Gehricke, & Galassetti, 2012). Experimental studies have shown that working memory tasks increase dopamine levels in the PFC, and obstructing dopamine receptors in the PFC creates working memory impairments (Durstewitz, Kelc, & Güntürkün, 1999). Given that individuals with ADHD often display impairments in working memory, these studies suggest that dysregulation of dopamine may correspond to the cognitive deficits observed in ADHD (Wigal et al., 2012). Specifically, it is hypothesized that attentional deficit may be caused by a hypodopaminergic state in the PFC (Solanto, 2002). Similarly, the noradrenergic system, which is involved in attention, working memory, and inhibition, is thought to be involved in the pathophysiology of ADHD due to low norepinephrine levels in the PFC being associated with deficits in working memory and EF (Arnsten, 2000; Pliszka, 2005). These studies of neurochemical dysfunction in ADHD are further supported by research on ADHD medications, which enhance levels of dopamine and norepinephrine in the PFC and ameliorate ADHD symptomatology (Pliszka, 2005).

COGNITIVE AND NEUROBIOLOGICAL EFFECTS OF PHYSICAL EXERCISE

Human and non-human animal studies have shown that PE results in short- and long-term neurobiological effects and can improve several aspects of cognitive functioning (for reviews, see Hillman et al., 2008; Loprinzi, Herod, Cardinal, & Noakes, 2013). PE has been hypothesized to be an effective therapeutic tool to target the neurobiological mechanisms associated with ADHD (Berwid & Halperin, 2012; Gapin et al., 2011; Wigal et al., 2012). The following section provides an overview of the cognitive and neurobiological effects of PE with a focus on components that underlie ADHD to identify theoretical mechanisms of change for PE interventions for emerging adults with ADHD.

COGNITIVE EFFECTS OF PHYSICAL EXERCISE

Several meta-analytic reviews have found positive associations between PE and cognitive functioning across the lifespan (Angevaren et al., 2008; Etnier, Nowell, Landers, & Sibley, 2006; Kramer & Erickson, 2007; Sibley & Etnier, 2003). However, the relation and improvements related to PE are not homogenous across domains of cognitive functioning. Across studies, PE consistently has been shown to disproportionally improve EF in children and adults (Hillman et al., 2008; Voss, Carr, Clark, & Weng, 2014). However, there is a relative lack of research on PE–induced cognitive effects in emerging adults. This is likely due to emerging adults often serving as comparisons for older adults and being near peak neurodevelopmental maturity (Giedd, 2004; Hillman et al., 2008). Existing literature indicates, however, that PE can yield cognitive benefits in emerging adulthood. A large cohort study demonstrated a positive association between PE and cognitive functioning in emerging adults (Åberg et al., 2009). Although information regarding influences on EF was not available for this study, PE was most strongly associated with logical reasoning, which contains components of EF. Additionally, Sibley and Beilock (2007) found that improvements in working memory were influenced by PE, but only for emerging adults who were impaired in this cognitive domain ($d = 1.22$). This suggests that PE may be uniquely beneficial for emerging adults with impaired cognitive functioning, such as ADHD.

Neurobiological Effects of Physical Exercise

Engaging in PE has a variety of effects on the brain's structure and functioning, including neurotransmitter and brain-derived neurotrophic factor (BDNF) levels, neurogenesis, synaptic plasticity, neuroendocrinology, angiogenesis, and cerebral blood flow (Voss et al., 2014). The neurobiological effects of PE are possible mediators of the benefits on cognition, particularly EF, observed in child and older adult populations (Hillman et al., 2008). Wigal and colleagues (2012) recently reviewed the theory that PE–induced effects in youth with ADHD are due to the effects that PE has on underlying neurophysiology of ADHD.

One hypothesis suggests that PE improves cognitive functioning through increased levels of norepinephrine, dopamine, and serotonin in the prefrontal cortex (PFC), striatum, and hippocampus (Ma, 2008; Meeusen & De Meirleir, 1995; Rommel, Halperin, Mill, Asherson, & Kuntsi, 2013). This hypothesis postulates that PE–induced increases in dopamine improve working memory, attention, focus, and learning. Increases in norepinephrine enhance attention regulation, working memory, and behavioral inhibition, while increases in serotonin may further facilitate improvements in attention, affect regulation, and inhibition of hyperactive/impulsive behaviors (Salmon, 2001; Wilens & Dodson, 2004; Winter et al., 2007). Thus, the increase in dopamine and norepinephrine associated with PE is similar to the effects of stimulant medications for ADHD (Pliszka, 2005).

It has also been suggested that the cognitive effects of PE may be explained by the upregulation of BDNF (brain-derived neurotrophic factor; Knaepen, Goekint, Heyman, & Meeusen, 2010; Ma, 2008; Rommel et al., 2013 Seifert et al., 2010; Wigal et al., 2012), which is a protein involved in the survival of neurons, synapse formation, and synaptic plasticity (Reichardt, 2006). BDNF plays a critical role in the differentiation and survival of dopaminergic neurons, hippocampal functioning, and long-term potentiation for learning and memory (Voss et al., 2014). Decreased levels of central BDNF activity have been purported to play a role in the pathogenesis of ADHD; BDNF knockout mice exhibit increased hyperactivity and cognitive impairment (Tsai, 2007). A recent study with humans supported the involvement of BDNF in ADHD, as genetic variants of BDNF are linked to ADHD symptoms (Bergman, Westberg, Lichtenstein, Eriksson, & Larsson, 2011). Similar to the physiological effects of stimulant and non-stimulant medication (Fumagalli et al., 2010; Meredith, Callen, & Scheuer, 2002), PE induces upregulation of BDNF and has therefore been thought to facilitate improvements in attention, inhibition, learning, memory, and mood (Hillman et al., 2008; Ma, 2008; Voss et al., 2014).

It should be noted, however, that these hypothesized neurobiological mechanisms of change are limited in that the research has largely been completed with rodents (Sontag, Tucha, Walitza, & Lange, 2010). More systematic studies of PE physiology in the context of ADHD in human samples are needed. However, as improved neuronal functioning is associated with remission of ADHD symptomatology (Bédard, Trampush, Newcorn, & Halperin, 2010; Halperin et al., 2008; Rommel et al., 2015; Shaw et al., 2013), PE has the potential of yielding enduring changes among those with ADHD (Berwid & Halperin, 2012; Halperin & Healey, 2011).

IMPACT OF PHYSICAL EXERCISE ON ADHD

A recent systematic review identified 21 studies examining the effects of PE in children and adolescents with ADHD (for a detailed review, see Neudecker et al., 2015). Research on the effects of PE intervention programs can be classified into two groups: acute and chronic. Studies of acute effects examine efficacy in terms of the effects of PE immediately following a single bout of activity, whereas chronic studies examine efficacy in terms of the cumulative effects of PE over a specified period.

Acute Effects of Aerobic Physical Exercise

In their review, Neudecker and colleagues (2015) identified six studies on the acute effects of aerobic PE in children and adolescents with ADHD. Aerobic PE included either treadmill running or ergometer cycling, with variability in duration and intensity between studies. Moderate-to-large effects were reported on aspects of EF following a 20- or 30-minute treadmill exercise in two studies (Chang, Liu, Yu, & Lee, 2012; Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013). High-intensity interval treadmill running (ten 2-minute running intervals with 1 minute of rest between intervals) also was found to have small to medium effects on several aspects of attention (Medina et al., 2010). Two studies reported that aerobic PE had small to large effects on neuroelectric measures of aspects of attention and dopaminergic activity (Pontifex et al., 2013; Tantillo, Kesick, Hynd, & Dishman, 2002), suggesting that aerobic PE may induce changes in brain activity. In the only study examining PE–induced changes in behavior, Flohr and colleagues (2004) reported significant reductions in disruptive behavior problems following 25 minutes of low to moderate ergonomic cycling. Finally, two studies using approximately similar aerobic PE duration and intensity exercises found changes in math and reading performance that were either large (Pontifex et al., 2013) or nonsignificant (Flohr, Saunders, Evans, & Raggi, 2004). Thus, whether aerobic PE can yield acute improvements in academic performance is unclear.

Chronic Effects of Regular Physical Exercise

Forming conclusions from the studies examining the chronic effects of PE in children and adolescents with ADHD is difficult due to the variability in PE regimens across studies. Studies can be categorized as either specific PE, sensorimotor PE, or mixed PE (Neudecker et al., 2015). For example, programs including tai chi would be classified as a specific PE (Hernandez-Reif, Field, & Thimas, 2001), programs focusing on perception and motor control would be classified as sensorimotor PE (Banaschewski, Besmens, Zieger, & Rothenberger, 2001; Park et al., 2013), and programs including multiple PE modalities such as aerobic and perceptual-motor water exercises would be classified as mixed PE (Chang et al., 2014).

All three categories of PE studies resulted in significant improvements on unblinded parent and teacher ratings of ADHD symptom severity in children and adolescents with ADHD (Ahmed & Mohamed, 2011; Banaschewski et al., 2001; Choi, Han, Kang, Jung, & Renshaw, 2015; Haffner, Roos, Goldstein, Parzer, & Resch, 2006; Hernandez-Reif et al., 2001; Hoza et al., 2014; Kang et al., 2011; Lufi & Parish-Plass, 2011; McKune et al., 2004), with small to large effects ($d = .26–2.39$). Most PE studies reported medium to large effect sizes on objective cognitive measures aspects of EF (*d* = .37–1.37), including attention and inhibition, in children and adolescents with ADHD (Chang et al., 2014; Choi et al., 2014; Haffner et al., 2006; Kang, Choi, Kang, & Han, 2011; Park et al., 2013; Verret et al., 2012), although two studies failed to detect effects of yoga on attention (Jensen & Kenny, 2004) and sensorimotor training on impulse control (Banaschewski et al., 2004). Lastly, results indicated that PE interventions for children and adolescents with ADHD can improve motor skill development and physical fitness, as evidenced by PE having moderate to large effects (*d* = .31–2.82) on measures of motor performance (Ahmed & Mohamed, 2011; Banaschewski et al., 2001; Chang et al., 2014; McKune et al., 2004; Pan et al., 2015; Verret et al., 2012).

Summary of the Impacts of PE on ADHD

Overall, the existing literature provides preliminary support for acute and chronic effects of PE on ADHD symptomatology and common areas of impairments in children and adolescents. In addition, PE has been associated with improvements on physiological measures associated with ADHD. However, there are no known studies demonstrating that improvements on physiological measures mediate improvements in ADHD symptomatology or impairments. Thus, it is unclear if observed improvements in impairment and symptoms are the result of changes in neurobiological factors. Most of these studies suffer from one or more limitations, such as limited sample size, subjective measures, nonrandom assignment, or absent or inadequate comparison groups.

PHYSICAL EXERCISE AS A POSSIBLE INTERVENTION FOR EMERGING ADULTS WITH ADHD

Although preliminary findings suggest that PE can have beneficial effects on the cognitive and behavioral functioning of children and adolescents with ADHD, it remains unknown whether the effectiveness of PE as a therapeutic tool varies across the developmental spectrum. Although it may be suspected that PE would yield the greatest effects during the developmental period in which the brain is most malleable, this notion has not been empirically tested. However, the PFC is among the latest neural structures to mature, continuing to develop throughout the mid-20s (Giedd, 2004), and increases in BDNF have been shown to be correlated with sustained attention among adults (Halperin & Healey, 2011). Evidence of the beneficial effects of PE on cognition in elderly adults (e.g., Angevaren et al., 2008) reinforces the possibility that PE could be beneficial for ameliorating core symptoms and impairments of ADHD beyond childhood.

While PE appears to be a plausibly *efficacious* intervention for ADHD in emerging adulthood, important consideration should be given to the degree to which it may be *effective*. That is, PE interventions may be efficacious in tightly controlled, ideal circumstances, but may not be effective in real world clinical settings. For those with ADHD, the transition to emerging adulthood is associated with almost complete treatment disengagement (McCarthy et al., 2009). Similarly, adherence to a regimen of consistent PE is notoriously poor over time (e.g., Garber et al., 2011). Unlike school-aged children who can have PE interventions incorporated into school schedules (Hoza et al., 2014) or are mandated by their parents to receive treatment, emerging adults must voluntarily engage, allocate time, and typically pay for treatments. Thus, it is important to consider the extent to which PE interventions can be effective outside of school settings. The following section outlines the research on PE interventions among adults with major depressive disorder (MDD) to inform the possible effectiveness of PE as an intervention tool for those with ADHD in emerging adulthood.

EFFECTIVENESS OF PHYSICAL EXERCISE INTERVENTIONS FOR MAJOR DEPRESSIVE DISORDER

The use of exercise in improving mental health is a growing research area that has documented positive effects across a variety of domains, including depression, anxiety, and stress (Salmon, 2001), as well as neurodegenerative diseases (Deslandes et al., 2010). Researchers cite the similar neurobiological mechanisms underlying the positive effects of PE for ADHD and MDD. This includes PE–induced increases in the synthesis and release of neurotransmitters and BDNF, which are thought to result in neurogenesis, angiogenesis, and neuroplasticity (Portugal et al., 2013). The mental disorder which has received the most research in PE is MDD. Theories underlying the pathophysiology of MDD often involve reductions of norepinephrine and serotonin (Lopez-Munoz & Alamo, 2009) and hypothalamic-pituitary-adrenal (HPA) axis hyperactivity due to increased levels of cortisol and corticotropic-releasing factor (Palazidou, 2012).

In follow-up studies, open trials, and randomized control trials, symptom reduction of MDD has consistently been correlated with regular PE (e.g., Blumenthal et al., 2007; Deslandes et al., 2010; Dunn, Trivedi, Kampert, Clark, & Chambliss, 2005; Singh et al., 2005). Both strength and aerobic PE evidence moderate improvements in MDD symptoms (standardized mean difference [SMD] = .61), with no significant differences between the two types of interventions (Silveira et al., 2013). Silveira and colleagues (2013) noted that a combination of moderate-intensity aerobic training and high-intensity strength training may provide more positive benefits than other PE regimens. While PE appears to be efficacious in reducing MDD symptom severity, the impact of PE is dependent upon level of adherence to a PE regimen (Portugal et al., 2013).

As alluded to previously, the positive mental health and cognitive effects associated with PE are predicated on regular engagement in PE (Garber et al., 2011), with high rates of *inactivity* attenuating beneficial effects (Guthold, Ono, Strong, Chatterji, & Morabia, 2008; Vayman & Gomez-Pinilla, 2006; Voss et al., 2014). The affective response to PE has been shown to predict the level of engagement 6 and 12 months after a PE session (Williams et al., 2008). In the case of aerobic PE, Ekkekakis and Petruzzelo (1999) suggested that the optimal intensity to provoke the most positive affective response is moderate to high and is near ventilatory threshold—the point at which oxygen delivery to muscles becomes a limiting factor (~65% VO_{2max}; Caiozzo et al., 1982). Aerobic regimens that tend to elicit positive affect include moderate aerobic PE that is below the ventilatory threshold (Reed & Ones, 2006). Although aerobic PE above the ventilatory threshold may be perceived as threatening and generate negative affective states (Ekkekakis, 2003), exercise regimens involving intervals of high-intensity aerobic PE elicit greater pleasure than continuous, moderate aerobic PE (Bartlett et al., 2011). In the case of strength training, little research has examined the optimal intensity to provoke the most positive affective response, with studies comparing low- and high-intensity strength training yielding inconsistent results (Portugal et al., 2013). Thus, there appears to be no consensus regarding the optimal strength training intensity on mood.

CLINICAL RECOMMENDATIONS FOR ADHD

Despite the absence of research documenting the effectiveness of PE in emerging adults with ADHD, there are numerous reasons for mental health providers to recommend PE as an adjunct to psychosocial and/or pharmacological treatments for clients of all ages. First, the existing literature in children and adolescents with ADHD provides evidence suggesting PE may yield improvements in cognitive and behavioral functioning in emerging adults. Second, regardless of ADHD status, PE is recommended for all adults to improve overall health and reduce the likelihood of future diseases (U.S. Department of Health and Human Services, 2008). However, PE is arguably more beneficial for emerging adults with ADHD due to their increased risk for poor health outcomes (Barkley et al., 2008; Nigg, 2013). Third, PE ameliorates depressive and anxiety symptoms (De Moor, Beem, Stubbe, Boomsma, & De Geus, 2006), both of which are commonly comorbid in emerging adults with ADHD (Meinzer et al., 2013; Milberger, Biederman, Faraone, Murphy, & Tsuang, 1995). Fourth, emerging adults with ADHD are 2 to 5 times more likely to experience sleeping problems (Gau et al., 2007), which may be improved by regular PE (Driver & Taylor, 2000). Although the plausibility of PE improving sleep patterns with ADHD samples has not been empirically tested, it is both relevant and important because a common side effect of stimulant medication is difficulty sleeping, which is negatively associated with mood regulation, academic performance, and domains of EF, including sustained attention, working memory, and inhibition (Danner & Phillips, 2008; Durmer & Dinges, 2005; Fafrowicz et al., 2010; Van Dongen et al., 2003). Lastly, for emerging adults without PE medical contraindications, safe levels of PE are a "do no harm" intervention tool with no known persistent adverse effects (Hoza & Smith, 2015, p. 4). In a similar vein, Arnold, Hurt, and Lofthouse (2013) have argued that some treatments are "safe, easy, cheap, and sensible (SECS) enough to be tried while awaiting better research" (p. 381). Thus, in spite of the limited evidence base, we are advising clinicians to consider including moderate-to-vigorous physical exercise as a recommendation for all clients with ADHD who have been approved for exercise by their physician.

FUTURE RESEARCH DIRECTIONS

Given that research on interventions for ADHD are scarce for emerging adults who often struggle during this developmental period (Fleming & McMahon, 2012; LaCount, Hartung, Canu, & Knouse, 2018) and that adjustment during this period tends to predict adaptive functioning in adulthood (Schulenberg, Sameroff, & Cicchetti, 2004), research exploring the potential benefits of PE in this population is warranted. Specifically, research is needed to test our aforementioned hypotheses regarding the possible effectiveness and efficacy of PE interventions for this age group. Relevant to PE interventions for ADHD among school-aged children and emerging adults, several critical questions remain:

1. What is the optimal dosage and modality of physical exercise and/or physical activity?
2. What is the minimum necessary intensity and duration needed to achieve a measurable and clinically significant effect (e.g., 30% symptom reduction; Zylowska et al., 2008)?
3. Are observed PE effects moderated by individual characteristics? In addition to the large variability in PE protocols, there was considerable heterogeneity between samples with a lack of consideration for important factors (e.g., medication status, comorbidities).
4. Will the impact of PE on cognitive function on laboratory and questionnaire measures generalize to real world benefits? For example, although cognitive training interventions for ADHD often report improvements in cognitive function and ADHD symptomatology, the improvements often fail to have ecological validity (Cortese et al., 2015).
5. Do physiological mechanisms mediate positive effects of PE on ADHD–related outcomes? In this respect, it is also important to consider other possible explanations for PE–induced improvements. It is often overlooked that many forms of PE require cognitive engagement (e.g., group games) that might explain improvements in cognitive function (Best, 2010). For example, it seems plausible that the mechanisms underlying the positive effects of PE may be similar to those of psychological mechanisms associated with mindfulness meditation training. Mindfulness meditation has been described as a psychological process that includes purposefully orienting attention to the present moment and approaching experiences in the present with curiosity, openness, and acceptance (Bishop et al., 2004). Although not empirically tested, it is intuitively plausible that, for example, engaging in moderate-intensity PE induces present-mindedness. Indeed, PE interventions and mindfulness meditation interventions cite a similar neurobiological mechanism (e.g., anterior cingulate cortex) to explain improvements in cognitive and behavioral outcomes among individuals with ADHD

(Mitchell, Zylowska, & Kollins, 2015).

6. What is the size of the effect and incremental benefit of PE relative to established ADHD treatments? Although existing studies have compared PE interventions against other interventions and included medicated and unmedicated samples, the individual and additive benefit of PE interventions to evidenced-based treatments for ADHD has not been systematically studied.

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